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HPP:TR 10

Harbor Protection Project
Yale University
New Haven, Connecticut

Technical Report No. 10
(HPP:510Ser 031)
30 July 1952

RADAR STUDIES OF MINE SPLASHES IN OPERATION MUD

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SECURITY INFORMATION

I. INTRODUCTION AND SUMMARY

1. The use of radar for spotting the splashes of air-laid mines is yet in an experimental stage. Some progress has been made in studies[1] of splash-target characteristics, and reasonably complete specifications for a splash-spotting radar can be set. However, experience in mine-splash spotting by radar is still very limited, and it is to be expected that other splash characteristics may be discovered which will strongly influence radar design. This report describes the results of radar tests in which the accuracy of location of splashes was investigated.

2. It was found that the radar echo of a mine-splash has an evolution or "drift" in space. Thus aside from any inherent errors in radar range and azimuth calibration, there exists an error due to ambiguity in relating the radar-target location with the water-entry point of the mine. In some cases, by analysis of visual motion pictures of the splash, this drift can be correlated with physical motion of the mine after its initial impact. Such ricochet and porpoising seems to depend on the water-entry angle and speed of the mine. In addition to these drift

1. Harbor Protection Project. Technical Report No. 5, HPP:510: Ser 319, dated 13 March 1952, a report of July 18-19, 1951, studies of mine splashes at the Chesapeake Bay Annex of the Naval Research Laboratory.

causes, which confuse visual spotting of the mine entry point as well as radar spotting, there is apparently a radar drift which is not observed optically. This phenomenon is associated with the persisting part of the splash echo and is probably due to drift of the spray.

3. When correct account is taken of the drift, the water-entry points of mines can be located to within a few yards with a suitable radar. In the present case the probable error in the radar entry point was about 25 yards, due in part to film reading inaccuracy. (On the radar scope the echoes were of dimensions 50 yd x 60 yd.) It does not seem reasonable to expect as good precision in an operational radar.

4. The tests described here were a part of Operation MUD[2] carried out during the period 3 December 1951 to 21 February 1952 at the Naval Mine Depot, Yorktown, Virginia. Only those parts of this operation which bear directly on the radar tests will be discussed here. A brief description follows.

5. In the tests the splashes of mines were located by radar and compared with the water-entry points as determined by optical triangulation. Except for the actual operation of the radar, all of the work and coordination of the radar tests was performed by Naval personel. The coordinator and sponsor of

2. See Harbor Protection Project, Technical Report No. 4 (HPP:100:Ser 00370) for a general description of Operation MUD.

Operation MUD was the Armament Branch of the Office of Naval Research. Officers of this Branch performed the planning and liaison duties. We are also indebted to the Naval officers and personnel of the Naval Schools of Mine Warfare, Yorktown, Virginia, and the Naval Mine Depot, Yorktown, Virginia, and in particular to Lt. Cdr. N. H. Prade of the Mine Service Test branch of the Naval Mine Depot. In addition to control of the aircraft, mine recovery, etc., officers and men of this group performed all of the construction, maintenance, and guarding duties in connection with the radar operations.

6. The radar used was the AN/MPG-1 which is an X-band rapid scan radar with rather high resolution in range and azimuth. The antenna scans at 16 per second over $\pm$ 5 degrees with a total 3 db beam width of 0.6 degrees. The pulse width is 0.25 microsec. and the pulse repetition rate is 4000 per sec. The video information is presented on a range-azimuth (B) scope. The range and azimuth coordinates of the center of the display are given by a precision dial system. Interpolation on the display is aided by azimuth marks at $\pm$ 1 degree and range marks at $\pm$ 1000 yd. In operation the display was centered on the echo of the raft used as a mine-laying target. The aircraft, falling mine, and splash appeared on the B-scope and were photographed with a 16mm motion picture camera. Range and azimuth relative

to the center of the display were scaled from these films. These measurements could be converted to absolute coordinates with a knowledge of the coordinates of the center of the display as derived from the radar dials or optical triangulation on the target raft.

7. In Operation MUD the water-entry points of the mines were located optically by a team of observers from the U. S. Navy Hydrographic Office under Mr. W. H. Atwood and Mr. W. J. Goodheart. In comparisons of radar and optical mine entry points their data were used to locate the radar site and to standardize the radar azimuth and range scales. All of this location procedure was made possible by the use of a precision coordinate grid set up for the York River area by Mr. Atwood's group. We are particularly appreciative of the extra work which they did in establishing the radar locations on this grid, and in supplying us with charts and coordinates of the various stations.

8. A list of the mine drops observed with the AN/MPG-1 appears in Table I. Figure 1 shows the operation area. Two radar sites were used as shown. The circled points are the positions of the target raft on the dates shown.

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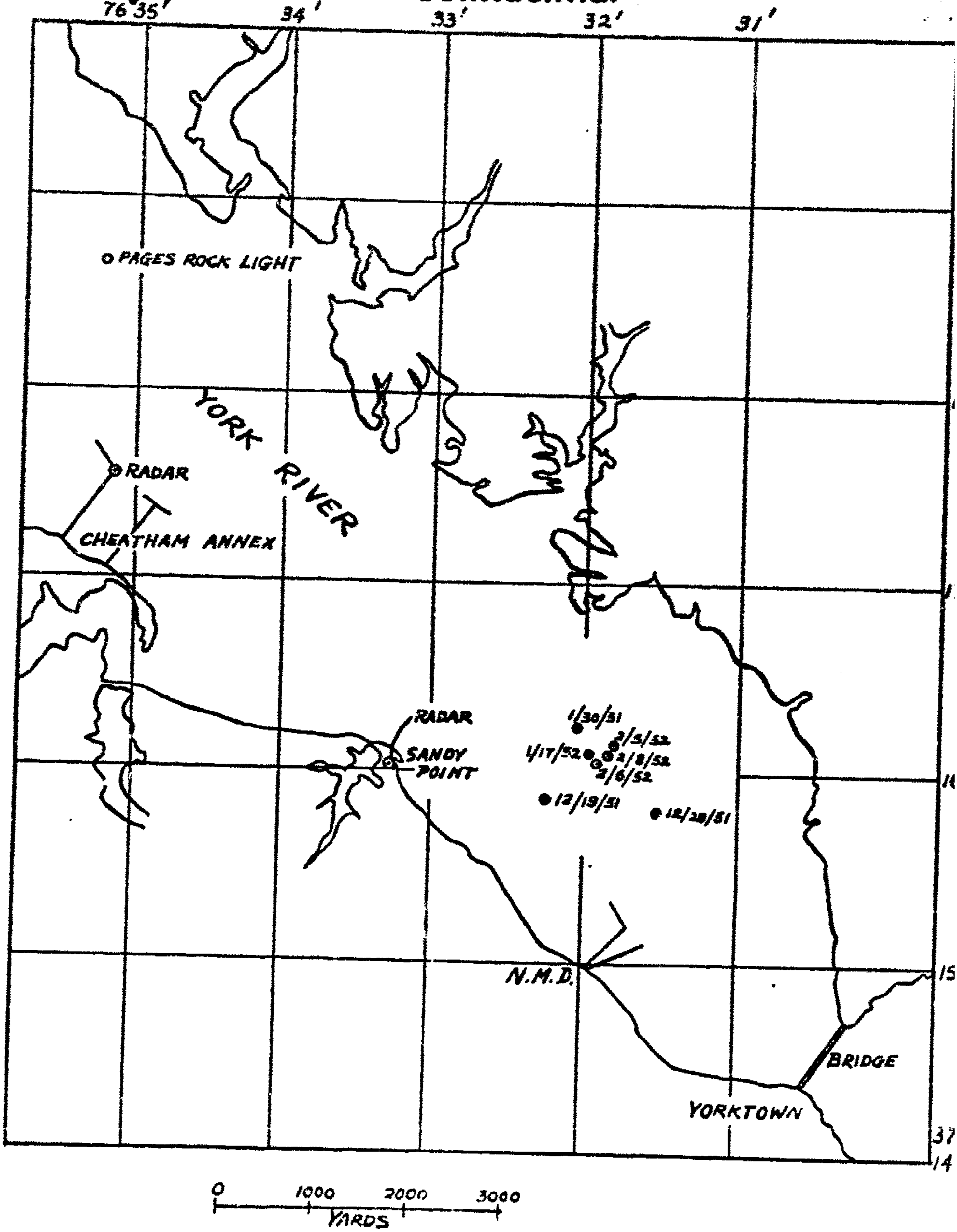


FIG. 1

Table I

Mine Drops Observed with an AN/MPG-1

Consecutive Drop No.	Date	Radar Run No.	Mine	Mine Release Speed	Alt.	Inclination	Radar Site
4	13 Dec.	4	36	270 kn	275 ft.	level	Sandy Point
5		5		270	250		
6		6		280	250		
7	14 Dec.	1	36	268	260	level	
8		2		280	220		
9		3		281	250		
10	19 Dec.	1	36	275	225	level	Sandy Point
11		2		290	250		
12		3		290	250		
13	28 Dec.	1	39	285	2000	45°	
14		2	39	250	3000	45°	
15		3	36	285	300	level	
32	17 Jan.	1	39	245	2000	50°	Cheatha
33		2		260	1600	20°	
34		3		305	3000	80°	
35		4		310	3000	70° to 80°	
36	30 Jan.	1	36	275	250	level	
37		2	36	290	300	level	
38		3	39	310	3000	75°	

Table I, cont.

Consecutive Drop No.	Date	Radar Run No.	Mine	Mine Release Speed	Mine Release Alt.	Mine Release Inclination	Radar Site
39		4	36	290 kn	300 ft	level	Cheatham
41		6	39	300	3000	70 to 80	
42		7	39	310	2800	75	
43	5 Feb.	1	39	180	350	level	
44	5 Feb.	2	36	260	280		
45	6 Feb.	1	39	260	220		
46		2		260	210		
47		3		258	240		
48		4		255	250		
49		5	36	300	260		
50		6		297	255		
51		7		240	250		
52		8	39	260	270		
53	8 Feb.	1		265	275	level	Cheatham
54		2		265	250		
58		6	25	260	250		
59		7	25	260	225		
60		8	36	295	200		

II. RADAR AND SPLASH LOCATION

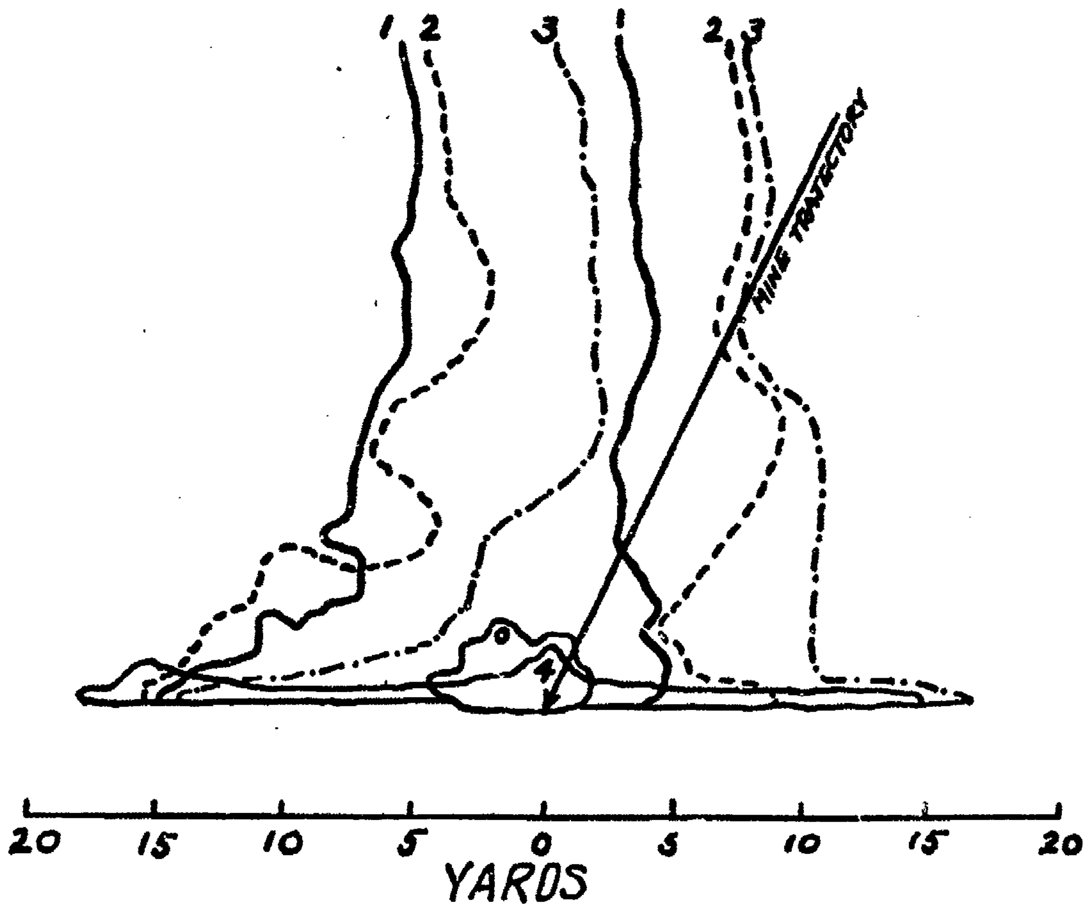
9. As mentioned in Paragraph 3 the principal object of the radar operation was to determine the precision with which mine entry points could be located by radar. This method consists essentially of a comparison of the location of the radar splash echoes with the mine entry points determined by optical triangulation. In addition to complexities introduced by the different coordinate systems of the radar and optical observations and by radar calibration errors in range and azimuth, there are several complexities due to the structure and evolution of the splash itself.

10. Unlike the mine-entry point, which can, in principle, be specified to within a region the size of a mine (e.g. 10 ft.), the splash is a relatively large object. Optical films of splashes show that they are frequently composed of several separate splashes, that the separate parts move away from the mine impact point, that the mine may plane or porpoise and create a wake of considerable size, or that it may ricochet and produce well separated multiple splashes. All of these possible courses depend on the operation of the parachute, if any, and on the speed and altitude of the mine-laying aircraft. These conditions are responsible for some of the effects noted in the radar splash observations. In essence, then, there is not a simple point target -- the splash -- uniquely related to the mine entry point, but a complex, evolving

target or targets. Figures 2, 3, and 4 are tracings of splashes photographed in Operation MUD. They show splash evolution in typical cases. In Fig 2 the mine made an almost vertical entry; the splash is also vertical. Fig 3, the splash from a mine of low entry angle, shows a forward motion of considerable extent. Fig 4 is a ricochet. These and similar optical splash analyses will be discussed further in paragraph 22.

11. As defined here, "drift" is the radar target evolution of a splash in range and azimuth due to ricochet, motion of the water and spray, porpoising, etc. While of interest to the radar spotter, it is only studied so that some method can be found to extrapolate to the mine entry point. If this method is found, a coordinate point can be specified as the best radar determined mine entry point.

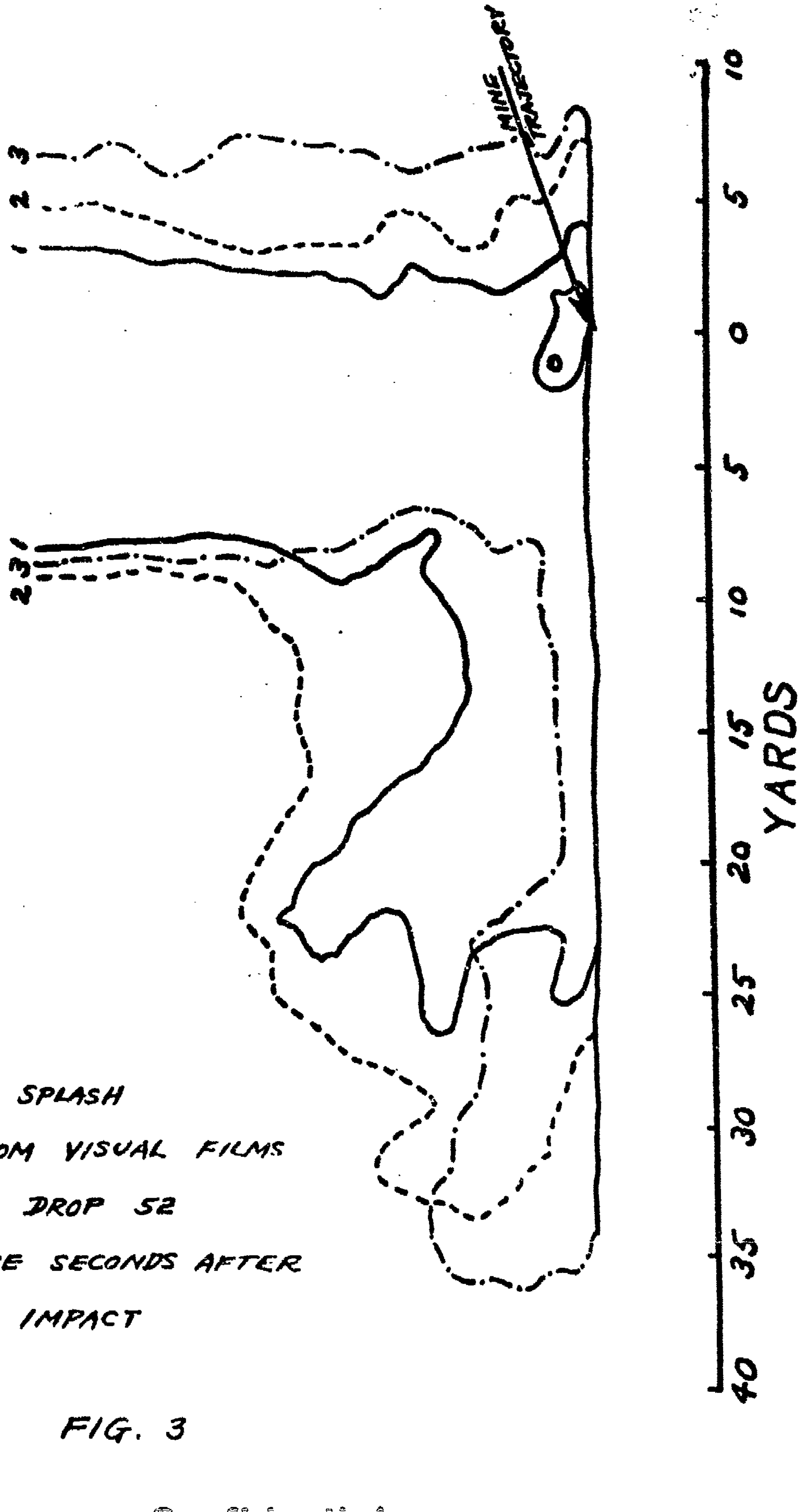
12. "Precision" is the accuracy with which the radar and optical mine-entry points agree. Lack of agreement is possible for numerous reasons; the drift may be incorrectly interpreted, the radar and optical spotting may refer to different parts of a complex splash, or the radar calibration may be in error. Also, the inherent radar accuracy due to beam-width and pulse-length sets a least-count error.



TRACINGS OF SPLASH OUTLINES FROM VISUAL FILMS JAN 30 DROP 41

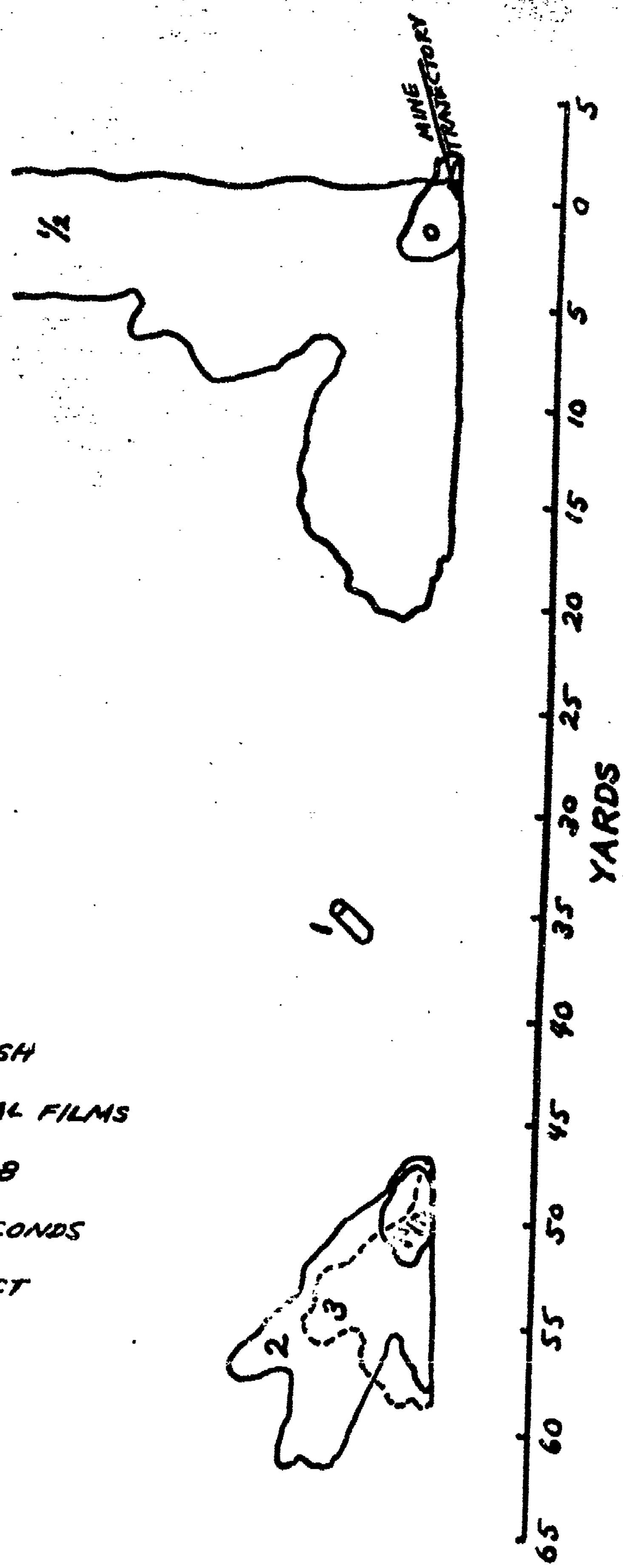
NUMBERS ARE SECONDS AFTER MINE IMPACT

FIG. 2



TRACINGS OF SPLASH
OUTLINES FROM VISUAL FILMS
FEB 6 DROP 52
NUMBERS ARE SECONDS AFTER
MINE IMPACT

FIG. 3



TRACINGS OF SPLASH

OUTLINES FROM VISUAL FILMS

FEB 6 DROP 48

NUMBERS ARE SECONDS

AFTER MINE IMPACT

FIG. 4

III. THE TARGET DRIFT

13. An analysis of the drift of the radar splash echo can be made independently of comparison with the optical mine-entry point, since all of the drift information appears on the B scope films in the local coordinate system of the target area. The drift is shown pictorially in Fig 5 which is a set of tracings of the radar echo from a splash. Similar results are shown in Figures 6 - 13 in which the target coordinates are plotted as a function of time. These were obtained by projecting single frames of the B scope spaced by one second intervals and measuring the range and azimuth of the intensity modulated signal relative to the target raft. In these measurements there is some difficulty in obtaining the true range of the target due to its changing strength and hence variable "blooming" on the scope. This was roughly corrected for by measuring to the lines of center of the splash-echo and of the target-raft echo. This procedure is not exact, due to asymmetry in the blooming of the echo, but is superior to use of the leading edge of the targets.

14. The plots of Figures 6 - 12 show echo locations spaced by 16 frames or one second. The zero time is arbitrary and in most cases occurs when the mine is in the air. The splash evolution begins at about one second in most cases shown.

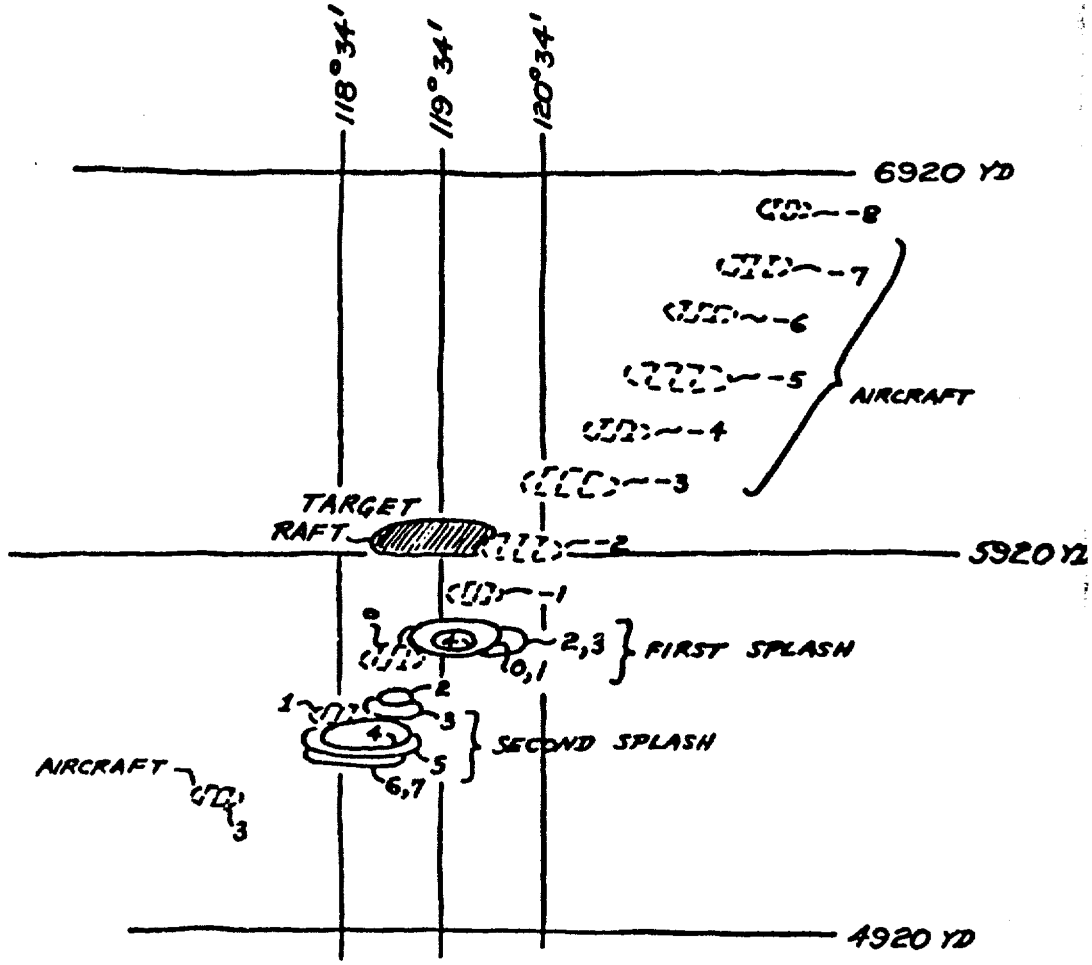
15. Figures 6 - 13 do not show all of the 37 drops listed in Table I. In drops 5, 6, 36, 46, 52, 54 the splash echo was masked by the echo of the target raft, making analysis of the splash evolution impossible.. In drop 38 the camera was started too late to show the mine entry. In drop 43 the splash was partly off the B scope screen.

16. Several generalizations can be noted from study of Figures 6 - 13.

A. The splash can be distinguished from the air-borne mine by noting a change in the rate of motion of the echo. There may also be a change in direction at the initial splash point. The mine in the air is seen to follow the aircraft course.

B. Large target "drifts" always show their principal motion in the direction of the aircraft course. In most cases this is due to ricochet and porpoising, which understandably preserve the forward motion of the air-borne mine; indeed these events do not occur except when a large forward velocity is present at water impact.

C. In addition to these large "drifts" due to motion of the mine after initial impact there exists another sort of drift persisting well after the water core of the splash has dissipated. This drift also generally shows forward motion but is less dependable in this respect. This drift of persisting echoes is probably due to motion of the spray.

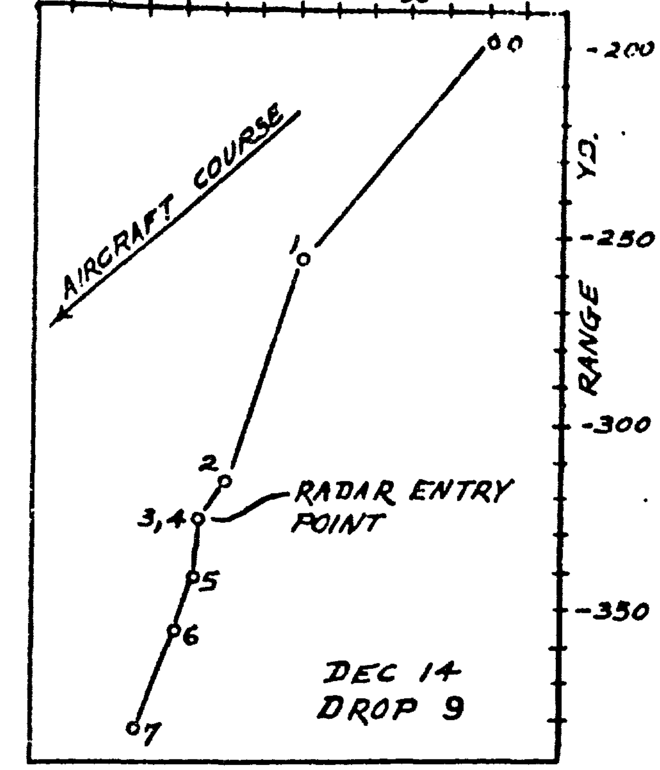


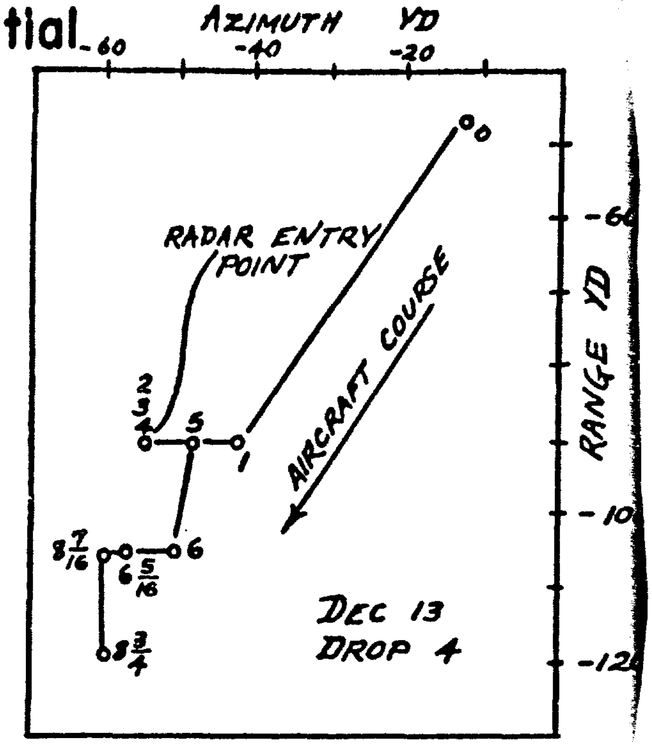
TRACINGS OF B SCOPE FILM. FEB 6, DROP 51
TIMES LABELING ECHOES ARE IN SECONDS (16 FRAMES)
ZERO TIME AGREES WITH FIG. 12

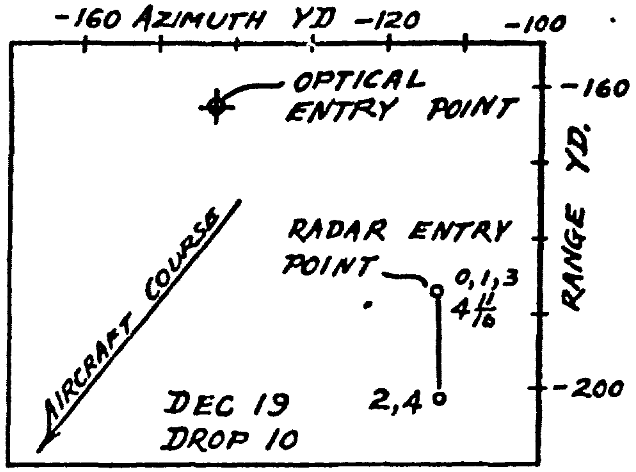
FIG. 5

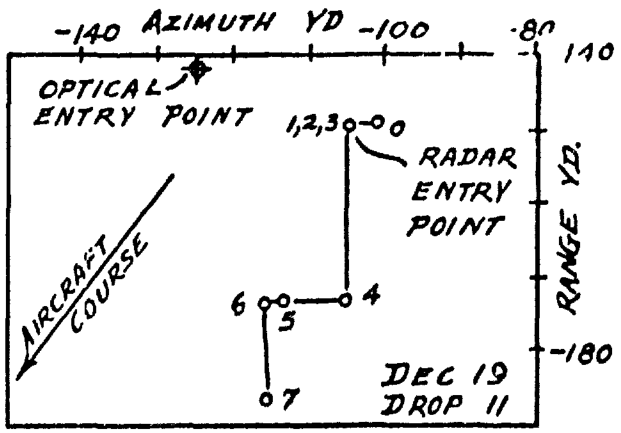
D. Some splashes show no "drift" larger than the reading errors due to the radar resolution. In some cases these have been correlated with optical observations which show compact, vertical splashes. It is probably safe to generalize from these cases.

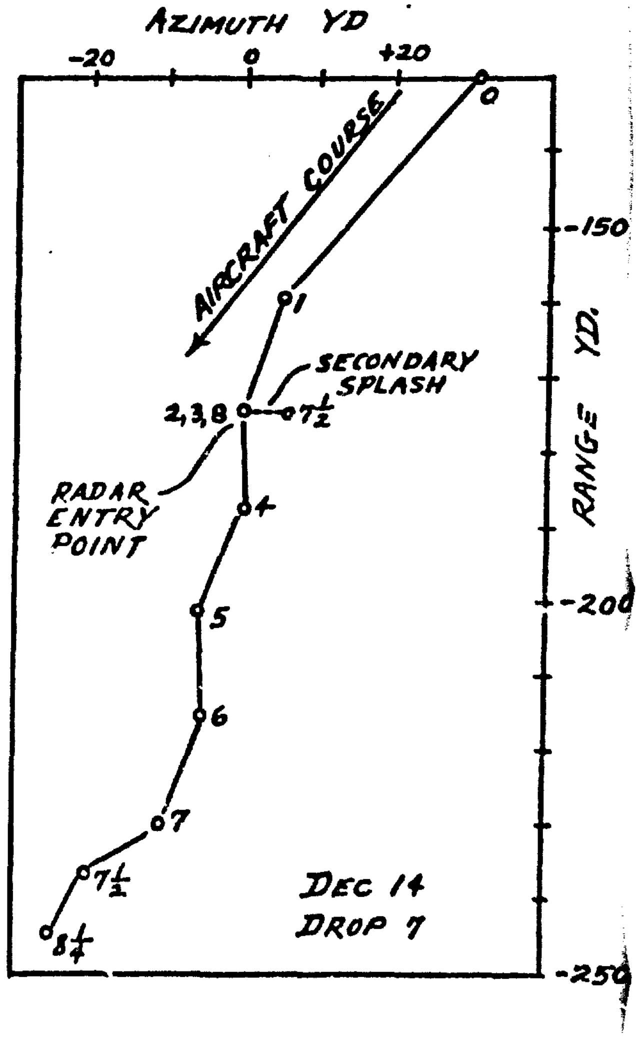
17. It should be pointed out that none of the drops in Operation MUD were made at high wind velocities. High winds would certainly modify the drift of the spray. There is some evidence that the drift of persistent echoes is correlated with wind direction in the present case.

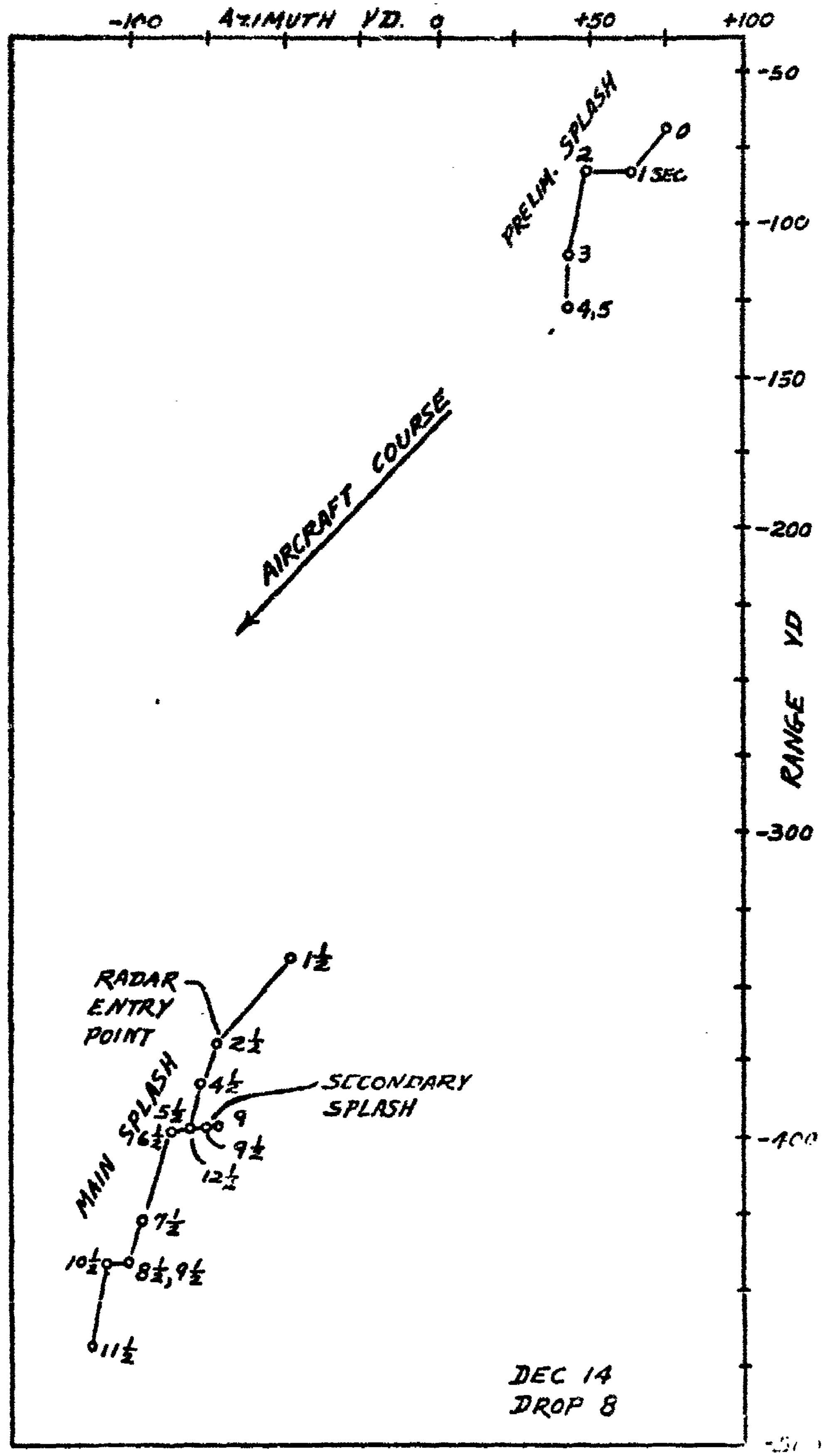

AZIMUTH YD
-150
-100
-50
-200
-250
-300
-350
RANGE YD.
AIRCRAFT COURSE
RADAR ENTRY POINT
0
1
2
3,4
5
6
7
DEC 14
DROP 9


AZIMUTH YD
-60
-40
-20
-60
-10
-12
RANGE YD
RADAR ENTRY POINT
AIRCRAFT COURSE
0
1
2
3
5
6
$6\frac{5}{16}$
$8\frac{7}{16}$
$8\frac{3}{4}$
DEC 13
DROP 4


-160 AZIMUTH YD -120
-100
-160
-200
RANGE YD.
OPTICAL ENTRY POINT
RADAR ENTRY POINT
0,1,3
$4\frac{11}{16}$
2,4
AIRCRAFT COURSE
DEC 19
DROP 10

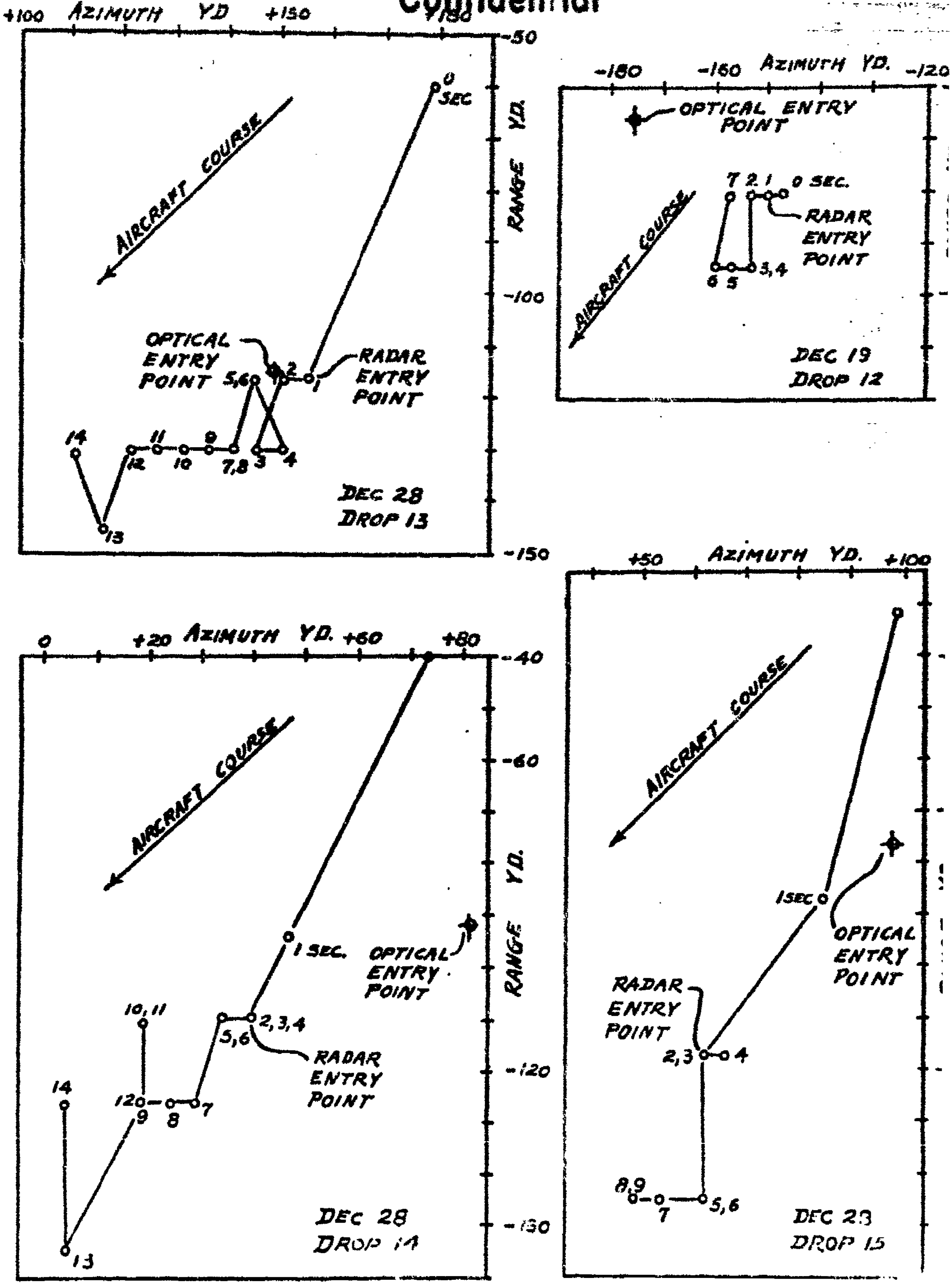

-140 AZIMUTH YD -100
-80
140
-180
RANGE YD.
OPTICAL ENTRY POINT
1,2,3
0
RADAR ENTRY POINT
AIRCRAFT COURSE
4
5
6
7
DEC 19
DROP 11


AZIMUTH YD
-20
0
+20
-150
-200
-250
RANGE YD.
AIRCRAFT COURSE
0
1
SECONDARY SPLASH
2,3,8
$7\frac{1}{2}$
RADAR ENTRY POINT
4
5
6
7
$7\frac{1}{2}$
$8\frac{1}{4}$
DEC 14
DROP 7



-100
AZIMUTH YD.
0
+50
+100
-50
-100
-150
-200
RANGE YD
-300
-400
PRELIM. SPLASH
0
1 SEC
2
3
4,5
AIRCRAFT COURSE
RADAR ENTRY POINT
1½
2½
4½
SECONDARY SPLASH
5½
6½
9
9½
12½
MAIN SPLASH
7½
10½
8½, 9½
11½
DEC 14
DROP 8

Fig



+100
AZIMUTH YD
+150
+180
-50
0 SEC
AIRCRAFT COURSE
RANGE YD.
-100
OPTICAL ENTRY POINT
RADAR ENTRY POINT
5,6
2
1
14
11
9
12
10
7,8
3
4
13
DEC 28
DROP 13
-150
-180
-160
AZIMUTH YD.
-120
OPTICAL ENTRY POINT
7 2 1 0 SEC.
RADAR ENTRY POINT
AIRCRAFT COURSE
3,4
6 5
DEC 19
DROP 12
0
+20
AZIMUTH YD.
+60
+80
-40
-60
AIRCRAFT COURSE
RANGE YD.
1 SEC.
OPTICAL ENTRY POINT
10,11
2,3,4
5,6
RADAR ENTRY POINT
14
12
9
8
7
-120
DEC 28
DROP 14
13
-130
+50
AZIMUTH YD.
+100
AIRCRAFT COURSE
1SEC
OPTICAL ENTRY POINT
RADAR ENTRY POINT
2,3
4
8,9
7
5,6
DEC 28
DROP 15

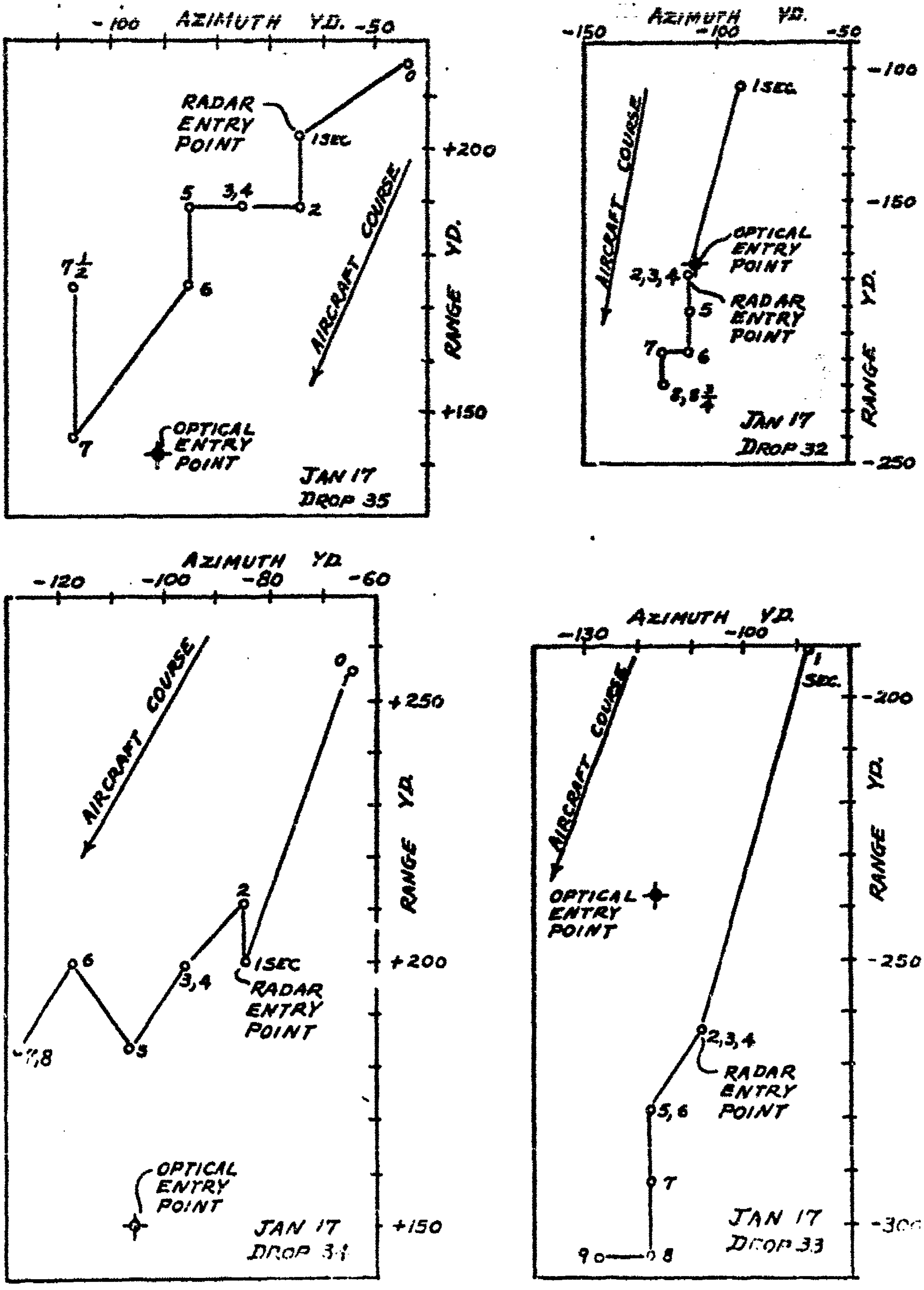
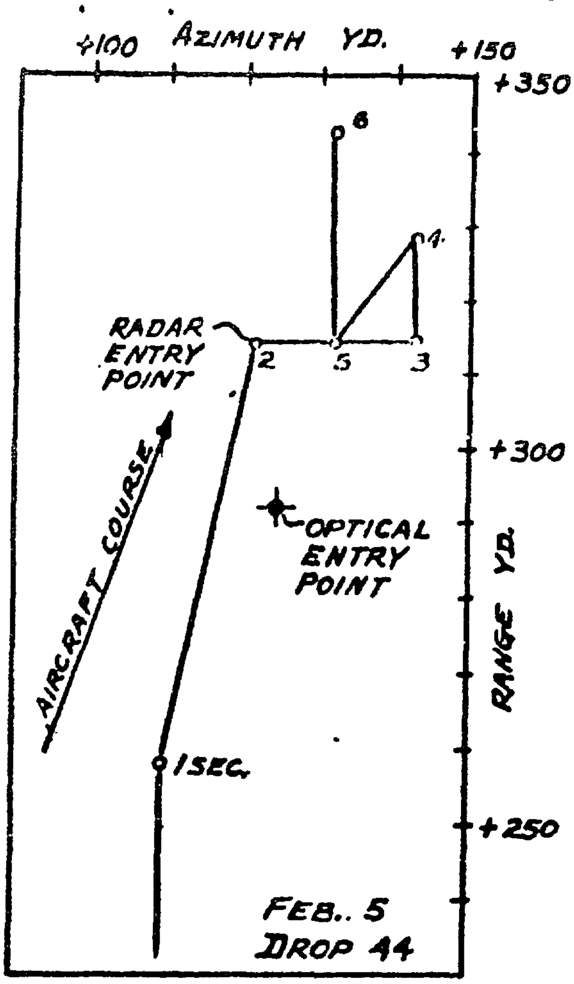
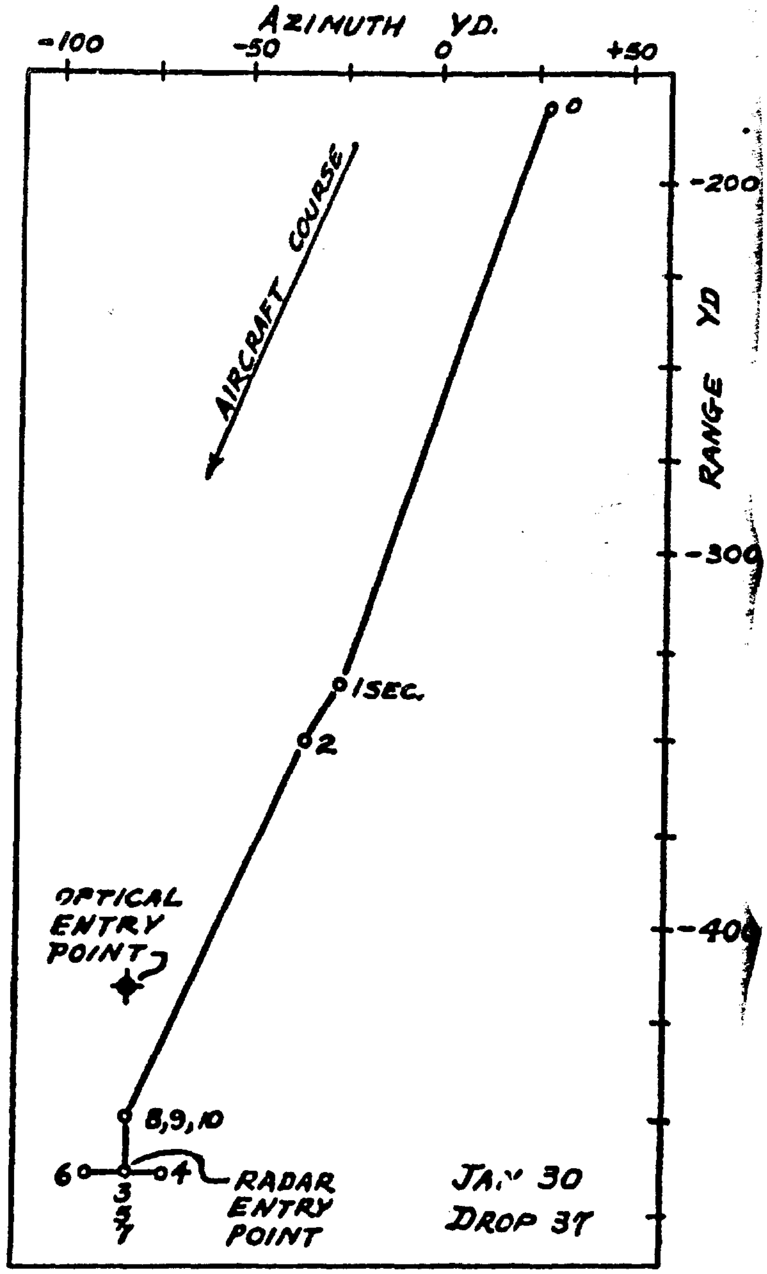
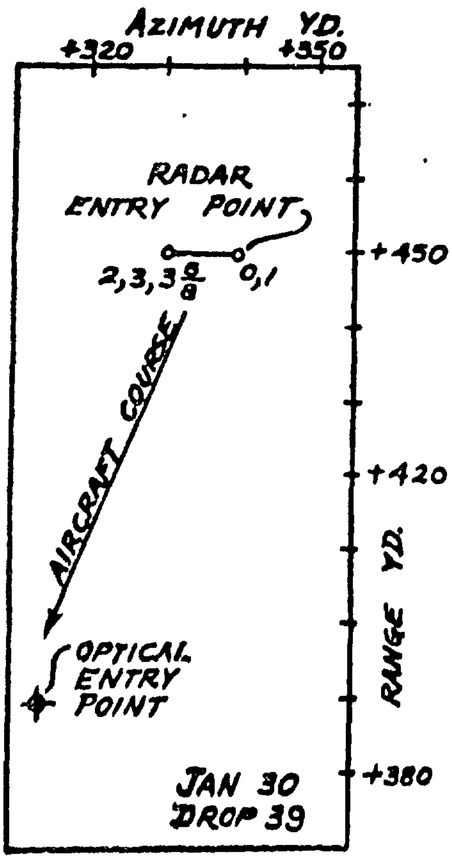
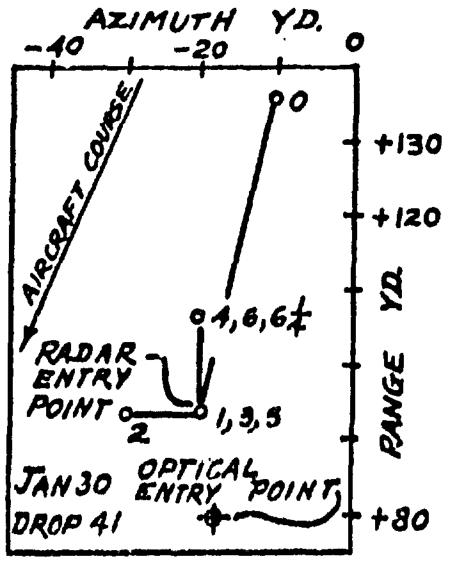

AZIMUTH YD.
RANGE YD.
RADAR ENTRY POINT
OPTICAL ENTRY POINT
AIRCRAFT COURSE
1 SEC.
JAN 17
DROP 35
JAN 17
DROP 32
JAN 17
DROP 34
JAN 17
DROP 33

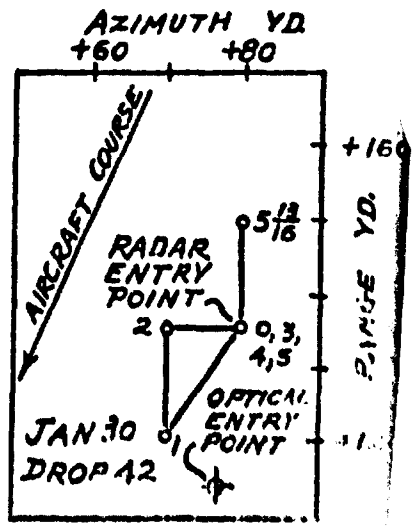
FIG. 9


AZIMUTH YD.
+100
+150
+350
+300
+250
RANGE YD.
6
4
3
5
2
RADAR ENTRY POINT
OPTICAL ENTRY POINT
AIRCRAFT COURSE
1SEC.
FEB.. 5
DROP 44


AZIMUTH YD.
-100
-50
0
+50
-200
-300
-400
RANGE YD
0
AIRCRAFT COURSE
1SEC.
2
OPTICAL ENTRY POINT
8,9,10
6
3
5
7
4
RADAR ENTRY POINT
JAN 30
DROP 37


AZIMUTH YD.
+320
+350
RADAR ENTRY POINT
2,3,3 5/8
0,1
+450
+420
+380
RANGE YD.
AIRCRAFT COURSE
OPTICAL ENTRY POINT
JAN 30
DROP 39


AZIMUTH YD.
-40
-20
0
0
+130
+120
+80
RANGE YD.
AIRCRAFT COURSE
4,6,6 1/4
RADAR ENTRY POINT
1,3,5
2
JAN 30
DROP 41
OPTICAL ENTRY POINT


AZIMUTH YD
+60
+80
+160
AIRCRAFT COURSE
5 13/16
RADAR ENTRY POINT
2
0,3,4,5
OPTICAL ENTRY POINT
1
JAN 30
DROP 42

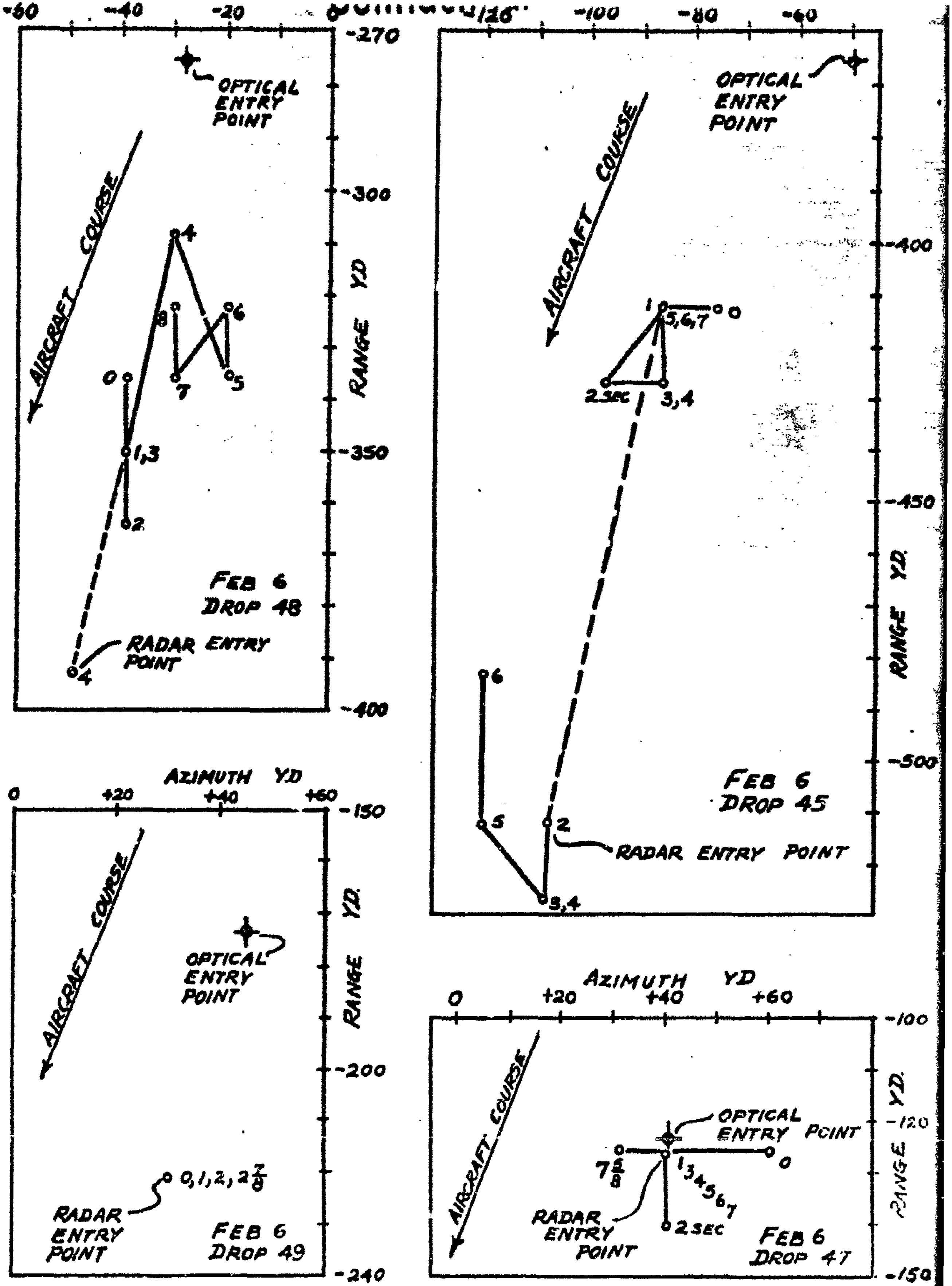

OPTICAL ENTRY POINT
AIRCRAFT COURSE
RANGE YD
FEB 6 DROP 48
RADAR ENTRY POINT
-270
-300
-350
-400
-60
-40
-20
OPTICAL ENTRY POINT
AIRCRAFT COURSE
5,6,7
2 SEC
3,4
RADAR ENTRY POINT
FEB 6 DROP 45
RANGE YD
-120
-100
-80
-60
-400
-450
-500
AZIMUTH YD
0
+20
+40
+60
-150
-200
-240
AIRCRAFT COURSE
OPTICAL ENTRY POINT
RANGE YD.
0,1,2,2 7/8
RADAR ENTRY POINT
FEB 6 DROP 49
AZIMUTH YD
0
+20
+40
+60
-100
-120
-150
AIRCRAFT COURSE
OPTICAL ENTRY POINT
RANGE YD.
7 5/8
2 SEC
RADAR ENTRY POINT
FEB 6 DROP 47

FIG. 11

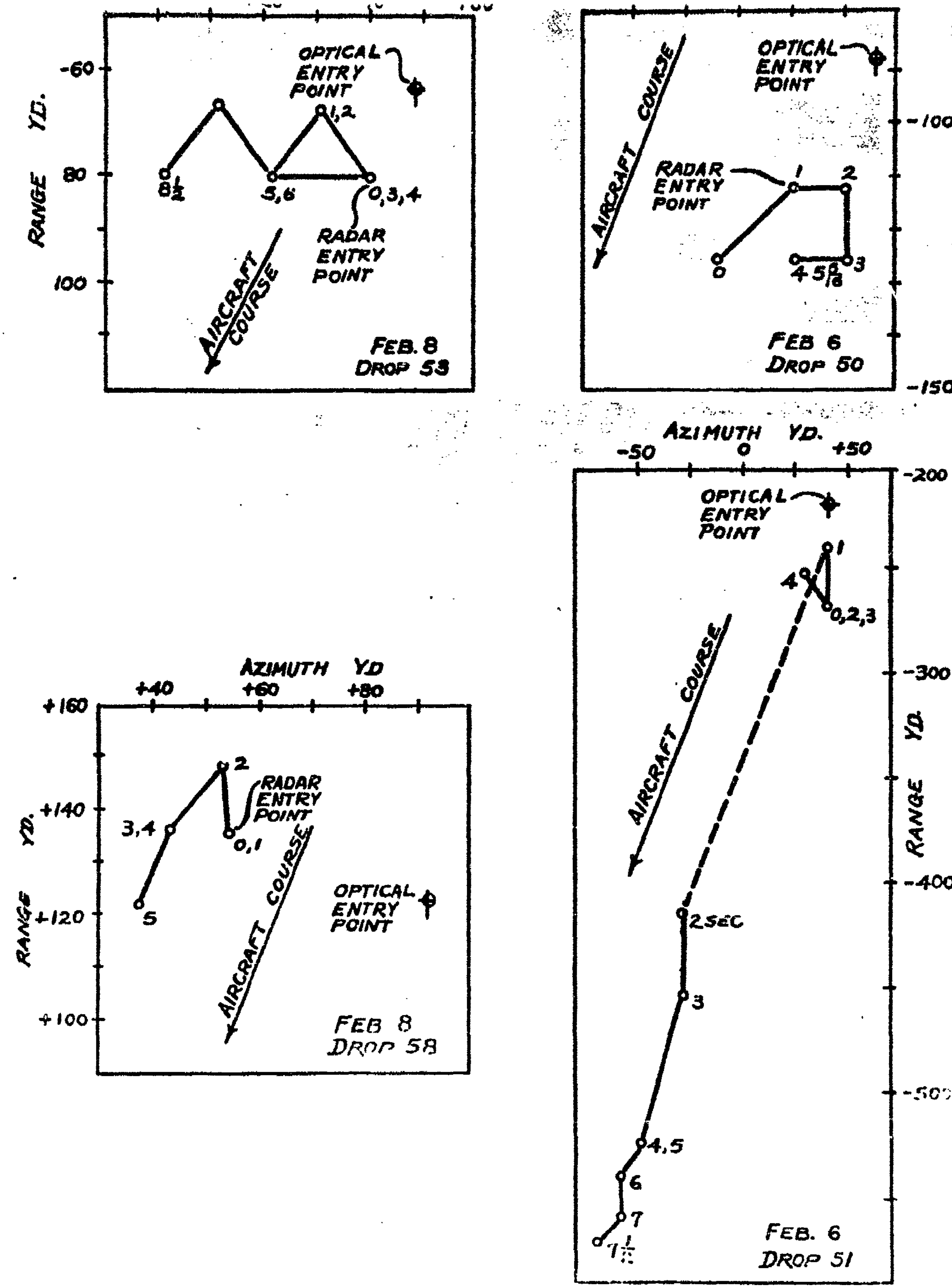
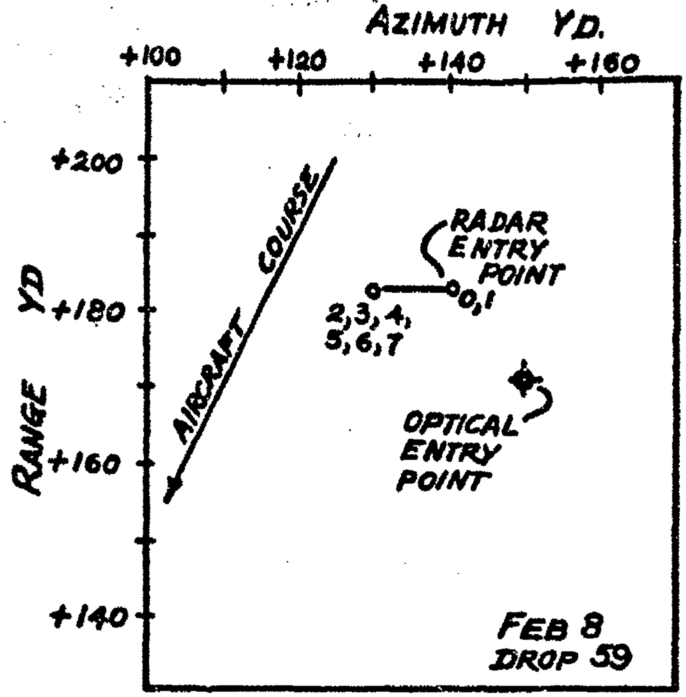

RANGE YD.
-60
80
100
OPTICAL ENTRY POINT
1,2
8½
5,6
0,3,4
RADAR ENTRY POINT
AIRCRAFT COURSE
FEB. 8
DROP 53
AIRCRAFT COURSE
OPTICAL ENTRY POINT
-100
RADAR ENTRY POINT
1
2
0
4 5
3
FEB 6
DROP 50
-150
AZIMUTH YD.
+40
+60
+80
+160
+140
+120
+100
RANGE YD.
2
3,4
RADAR ENTRY POINT
0,1
5
AIRCRAFT COURSE
OPTICAL ENTRY POINT
FEB 8
DROP 58
AZIMUTH YD.
-50
0
+50
-200
OPTICAL ENTRY POINT
1
4
0,2,3
-300
AIRCRAFT COURSE
RANGE YD.
-400
2 SEC
3
4,5
6
7
7½
FEB. 6
DROP 51

FIG. 12


AZIMUTH YD.
+100
+120
+140
+160
RANGE YD
+200
+180
+160
+140
AIRCRAFT COURSE
RADAR ENTRY POINT
0,1
2,3,4,
5,6,7
OPTICAL ENTRY POINT
FEB 8
DROP 59

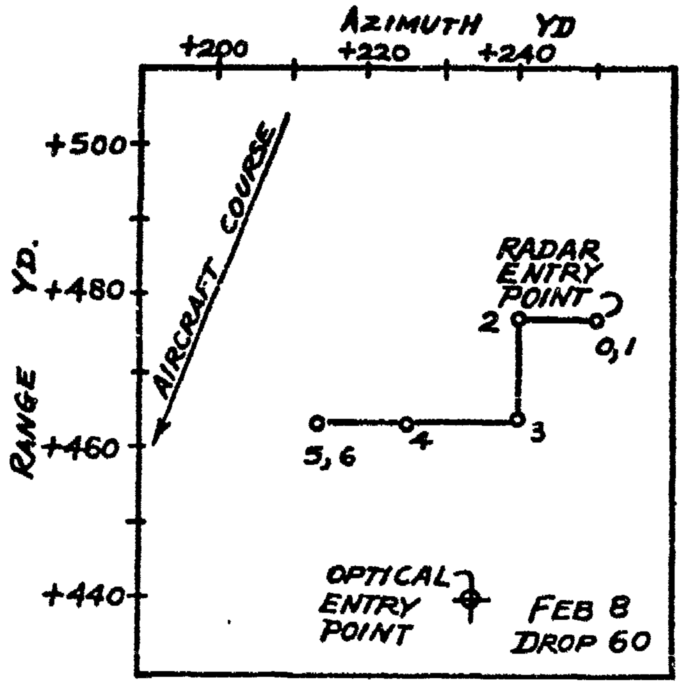

AZIMUTH YD
+200
+220
+240
RANGE YD.
+500
+480
+460
+440
AIRCRAFT COURSE
RADAR ENTRY POINT
2
0,1
3
4
5,6
OPTICAL ENTRY POINT
FEB 8
DROP 60

FIG. 13

IV PRECISION OF MINE-ENTRY LOCATION

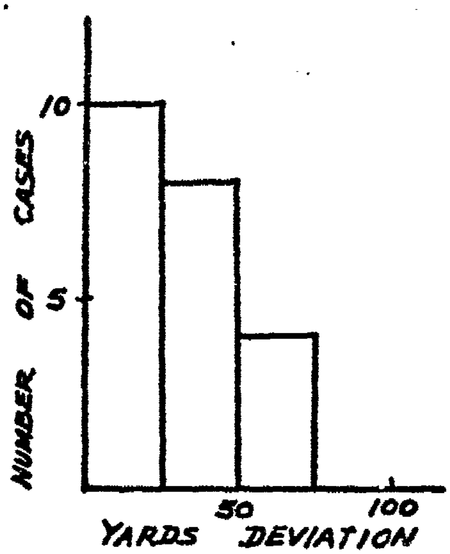
18. The precision of location of the water-entry points of mines by radar is best illustrated by reference to Figures 6 - 13. Here we have plotted the optically determined water-entry points as calculated from the triangulation data of the Hydrographic Office team. The target raft is used as the origin in these plots. On the same plots are indicated the radar determined mine-entry points. These were chosen at the junction between the end of the rapid motion of the target (indicating the air-borne mine) and the beginning of the splash evolution. In many cases this point is unambiguous from the plots, but in other cases it is not, because of ricochet and porpoising of the mine.

19. The radar data of Figures 6 - 13 were not plotted directly from the range and azimuth dial readings, which were subject to calibration errors, but were standardized by use of the optical location of the target raft. That is, the coordinates of the center of the radar display, which is the echo of the raft, were taken from the optical location of the raft. The mine and splash echoes were determined with reference to the center of the B display by measurement of the film records. In other words, the coordinate systems of the radar and of the optical triangulation were made to agree at one point -- the target raft. The errors introduced by the dial calibration were not large, about 0.2

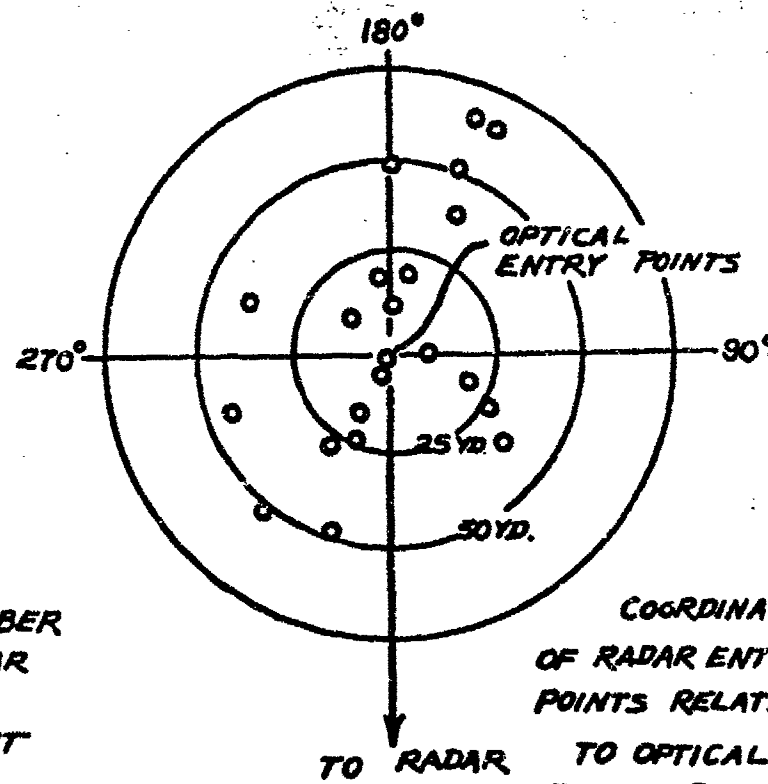
degree in azimuth and 60 yd in range, but it did not seem advisable to use these raw data in the present comparisons. In an operational use of splash-spotting radar, calibration errors would probably be eliminated by a similar procedure.

20. The accuracy of the radar location of mine-entry points is collected in Figure 14 which is a polar plot of the radar entry points relative to the optical entry points. Twenty-two cases are plotted; it is seen that the probable error is 25 yards. This is close to the reading error of the radar data.

21. In plotting Fig 14 certain of the drops of Table I were rejected as unsuitable. Drops 4, 5, 6, 7, 8, 9 were not included because of the lack of optical data on the target raft. Table II lists the results of graphical analysis of these runs using the optical entry points together with the radar entry points as determined from the range and azimuth dials.



DISTRIBUTION IN NUMBER OF DEVIATIONS OF RADAR ENTRY POINTS FROM OPTICAL ENTRY POINT



COORDINATES OF RADAR ENTRY POINTS RELATIVE TO OPTICAL ENTRY POINT

FIG 14

TABLE II

Consecutive Drop Number	Yards deviation of radar entry point relative to optical entry point
4	20 yd
5	90
6	60
7	10
8	60
9	20

Other drops listed in Table I and rejected for Fig. 14 were:

Drop 36 - Splash obscured by target raft echo, deviation 60 yd from graphical analysis.

38 - Camera started too late to get entry, deviation about 150 yd.

43 - Splash partly off screen. Poor optical data, deviation about 60 yd.

46 - Splash obscured by target raft echo, deviation about 40 yd.

52 - Splash obscured by target raft echo, deviation about 40 yd.

54 - Splash obscured by target raft echo. Poor optical data, deviation about 40 yd.

45, 48, 51 - Ricochet. Optical entry points apparently chosen at first impact rather than final entry.

22. The effects of forward motion of the splash for mines of low entry angle and of porpoising and ricochet have been mentioned in paragraph 10. Figures 2, 3, 4 illustrate these effects. Unfortunately, not all drops of interest were photographed visually in such a manner as to permit determination of time and distance scales for the splash evolution. However, in those cases where the splash could be plotted, as in Figures 2, 3, 4, there was a definite correlation with the radar data. Table III summarizes this information. In these visual splash plots the mine case was used to establish the distance scale and the velocity of the air-borne mine established the film frame-speed, and hence the time scale.

TABLE III

Consecutive Drop Number	Comments
14	Visual film shows compact splash, about 15 yd forward motion at 4 sec. The drift of the persistent radar echo is large but occurs after the splash is terminated optically. Probably due to spray.
41	Compact vertical splash (Fig 2). Also no appreciable radar drift.

TABLE III, cont.

Consecutive Drop Number	Comments
48	Short ricochet (Fig 4) about 50 yd. Ricochet indicated in radar data by weak second target appearing 50 yards forward at 4 sec. Long time backward drift probably spray.
52	40 yd. splash motion forward (Fig 3). No radar data due to masking of splash by target raft.
53	30 yd forward splash motion. Small short time radar drift also.
58	20 yd forward splash motion. Small radar drift also.
59	20 yd forward splash motion. Small radar drift also.
60	20 yd forward splash motion. Small radar drift also.

V CONCLUSION

23. This report shows that the water-entry points of air-laid mines can be determined to good precision (probable error 25 yd) by radar. However, there are a number of effects which

confuse radar location. Some of these are associated with mult-iple splashes due to ricochet and porpoising of low entry-angle mines. There is also frequently a long-time drift associated w splash targets which persist after the water core of the splash has dissipated. This is probably due to the physical motion of spray.